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COMPLEMENTARY INFORMATION FROM mm-WAVE-, INFRARED- AND GAMMA RAY ASTRONOMY

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I. INTRODUCTION

Infrared- and gamma-ray astronomy are similar in both their technical challenge and their unique scientific promise. The technical challenge arises from the need for complicated space-borne instrumentation like sizeable sparkchamber telescopes on one side, kryogenic telescopes and detectors on the other, and complex techniques of background rejection, necessary in both regimes. The enormous promise of IR and gamma-ray observations is the absence of extinction and unique information not available in any other wavelength range such as the Visible, UV, X-Ray or conventional Radio window.

Infrared astronomy is particularly well suited to study the physical condition (temperature and density) of the interstellar matter in our galaxy and in external galaxies, and the investigation of the cosmological 3K background radiation which, of course, has its maximum spectral density in the Far-Infrared. This leads to a first albeit less important connection because the 3K background is partner in the gamma-ray production through the inverse Compton process.

Table 1 gives an overview of the subdivision of wavelength ranges, importance of extinction, observing techniques and scientific objectives in both IR broadband measurement and spectroscopy. It is interesting to see how the extinction by interstellar dust, which adds up to 40 magnitudes in the Visible, decreases with increasing wavelength. In the Far-Infrared there is virtually no extinction throughout the galaxy a fact that also holds for gamma ray astronomy.

II. INFRARED AND mm-WAVE SPECTROSCOPY IN THE GALAXY

The importance of MIR and FIR dust emission, as measured by IRAS (Neugebauer et al., 1984) will be addressed by Stecker in the next paper. Therefore, I shall skip this topic for the sake of shortness. A review is given e.g. by Cox and Mezger, 1989.

Infrared spectroscopy may be less common knowledge and seems to be of considerable importance for gamma-ray astronomy because it provides specific information on temperature, density, molecular abundances and chemistry of interstellar gas. NIR lines, as listed in table 1, are emitted by ionisation regions and, as far as molecular lines are concerned, from shock-exited hot gas. A spectrum of the Orion KL source (fig. 1, taken from Watson, 1982) illustrates the wealth of information available at infrared and millimeter wavelengths. We recognize that emission lines are most numerous and intense in the FIR. FIR fine structure lines are excited by the photo electric effect (Tielens and Hollenbach, 1985) whereas molecular line emission is excited by collision with hydrogene and intensity ratios of lines from different species or different transitions from one species allow to determine density and temperature. For example the 63 μm OI/158 μm CI ratio is not much dependent on temperature and probes density whereas the 63 μm OI/145 μ OI ratio probes temperature because of different exitation energy. For standard line ratios not even a compilation is necessary because density and temperature can be taken from diagrams (Watson, 1982) where care must be taken, of course, that line emission is not received from two or more sources in the beam. Fig. 1 indicates also that the rotational ladder of CO starting with the lowest transition at 2.6 mm wavelength extends up into the FIR. These higher transitions are intersting because they are emitted by dense warm clumps in star formation regions. For a given telescope higher

TABLE 1

OVERVIEW ABOUT INFRARED ASTRONOMY

Wavelength ranges	near infrared (NIR)	mid infrared (MIR)	far infrared (FIR)
wavelength	1 to 5 μm	5 to 30 μm	30 - 300 μm
extinction towards gal. center ($A_{vis} = 40^m$)	20^m to 4^m	4^m to 0.7^m	negligible
typical objects	stars	imbedd. stars, warm dust, ice and silicon features, radiation from PAHs	cold dust, protostars?, galaxies, cosmological background
observations	ground based in atmosph. windows	ground based in very few atmosph. windows, spaceborne telescopes	no atmosph. windows, airplane-, balloon, satellite-measurements, <u>cooled</u> telescopes
spectroscopy	HI Spectrum (Paschen, Bracket, Pfund Series) Br α 4.06 μm Br γ 2.17 μm V-r transitions of H_2, CO	Fine Structure Lines SIV 10.6 μm NeII 12.6 μm V-r transitions of CO_2, NH_3, SiH_4, etc.	Fine Structure Lines CI, CII, OIII, etc. rotational transitions CO, ^{13}CO, $C^{18}O$ NH_3, HCN, HCO^+, OH, etc.

transitions at shorter wavelengths also allow for better angular resolution. Molecular hydrogene, present in dense and massive clouds in the galactic plane, is probably the most important component of interstellar matter. Gamma radiation is produced in these clouds by cosmic radiation through the π_0 decay. This radiation, addressed in a separate paper by Hunter in this symposium, is a major part of the resolved gamma radiation from the galactic disc as observed by SAS-2 and COS-B. Cosmic radiation not only produces gamma rays, it also is partly responsible for the synthesis of complex molecules in the clouds by the introduced ionisation because in the gas phase molecules form almost exclusively through ion reactions.

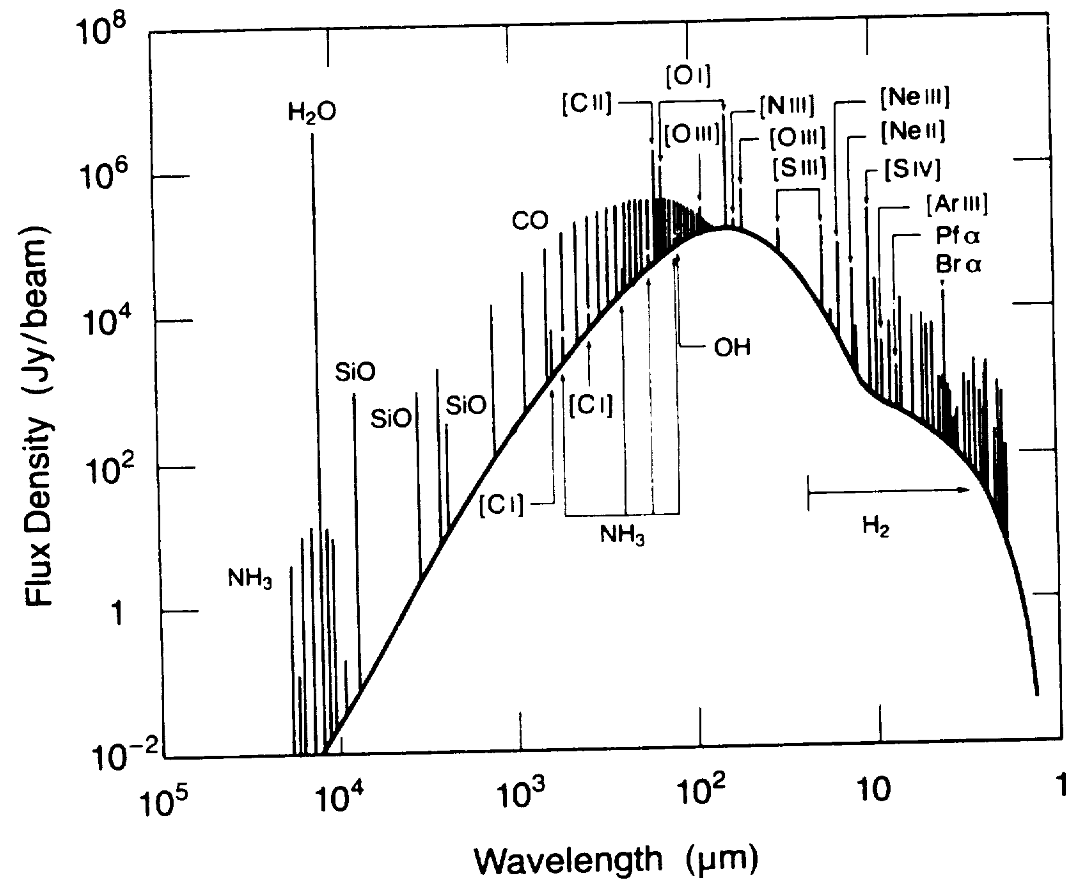


Fig. 1 Spectrum of the Orion KL source from 1 μm to 10 mm wavelength taken from Watson, 1982.

The line emission of the lowest rotational transition of CO at 2.6 mm wavelength is considered to be the workhorse to trace molecular hydrogene. However, H_2 column density does not follow directly from the observed ^{12}CO (1-0) line flux because the line is saturated and its exitation depends on density and temperature in the emitting region. Furthermore, the molecular abundances are not certain. If there are no additional observations of isotopic CO lines and other rare molecules probing for optical depth and density and of higher rotational transitions of CO at submillimeter or FIR wavelengths, probing for gas temperature, the H_2 column density cannot be computed reliably from 2.6 mm data. Without this additional information an empirical calibration factor has to be used to convert the 2.6 mm line flux into H_2 column densities. As addressed already by Thaddeus in the first talk, a number of methods are used to find this calibration factor at specific sources where the H_2 column density or mass can be determined by an independent measurement such as visual extinction or virial theorem. (For references see e.g. Van Dishoeck and Black, 1987). Where H_2 column density is evaluated from extinction, IR measurements are attractive because extinction, derived in the Visible by star counts or other methods, can be measured directly by multiple wavelength IR photometry on the basis of a well established wavelength dependence of extinction (table 1). A self consistent model for HI, CO and resolved gamma ray emission has been presented which results in the above calibration factor under certain assumptions on the distribution of cosmic rays (Black and Fazio, 1973; Lebrun et al., 1983; Bloemen et al., 1984, 1986; Blitz et al., 1985; Li, Riley, and Wolfendale, 1983; Riley et al., 1984; Bhat et al., 1985; Bhat, Mayer, and Wolfendale, 1986). If the hydrogene density could be determined reliably through independent methods such as submillimeter- and IR spectroscopy the above model could produce detailed information about the distribution of cosmic radiation in the galaxy.

An interesting question for gamma ray astronomers is whether FIR- and mm-spectroscopy could determine ionisation rates produced by cosmic radiation and UV radiation of young stars. A number of emission lines of ionized molecules (e.g. HCO^+) can be measured, however, so far no line could be identified as a specific tracer for ionisation because apart from H_2 all molecules known are formed through the ionisation channel since ions have a larger reaction rate.

III. IR- AND mm WAVE-OBSERVATIONS OF CENTAURUS A

The rest of this paper is dedicated to an extragalactic source. Nearby external galaxies, even if they are not of a merging or starburst type, are very attractive because they give us a global picture with kpc resolution from an outside point which is essentially impossible to derive from our own galaxy. Centaurus A is a giant elliptical galaxy which has been studied at almost any accessible wavelength range because it is the nearest radio galaxy and has a prominent dust lane. Using the recently established 15 m SEST telescope in La Silla (Chile) the galaxy was mapped in its 2.6 mm CO emission. In addition spectra of the J = 1-0 and J = 2-1 transition of ^{12}CO and ^{13}CO and an upper limit for J = 1-0 of $C^{18}O$ were obtained at selected positions. The ^{12}CO (1-0) contour radio map is shown as an overlay on the optical plate (fig. 2) with the continuum radio source removed from the data.

Maps of Cen A taken at 50 and 100 μm with the IRAS CPC are shown in fig. 3. Both radio and infrared emission are well aligned with the dust band. If the infrared emission is due to dust heated by UV radiation of young stars and if CO emission traces molecular gas, available for star formations, the ratio of IR luminosity over molecular mass is a measure for star formation efficiency (SFE). For Cen A a SFE of 18 Solar luminosities per Solar mass are found, a value which agrees with the canonical number for isolated galaxies (Young and Sanders, 1986). Starburst galaxies would have a 10 times higher star formation efficiency and probably a accordingly higher Supernova rate and diffuse gamma ray flux. If the diffuse gamma radiation of Cen A would be comparable to the flux measured towards the galactic center by SAS-2 and COS-B the 30" by 180" source is diluted by a factor of 10 000 considering the angular resolution of the EGRET sparkchamber telescope. This flux is clearly not detectable.

Nevertheless, besides upper limits from SAS-2 and COS-B (Bignami et al., 1979 and Pollock et al., 1981) detection of a gamma-ray continuum from Cen A is claimed on a 4 σ level by Ballmoos, 1985 and Grindlay et al., 1975 as well as detection of gamma ray line emission on a 3 σ level by Hall et al., 1976. To examine these marginal detections Cen A probably should be revisited by the EGRET instrument. A significant upper limit or a reliable detection of gamma radiation might contribute important information on the nature of the source.

Fig. 2 Cen A optical plate with the 2.6. mm CO emission contours overlaid (Eckart et al., 1989 and 19990a).

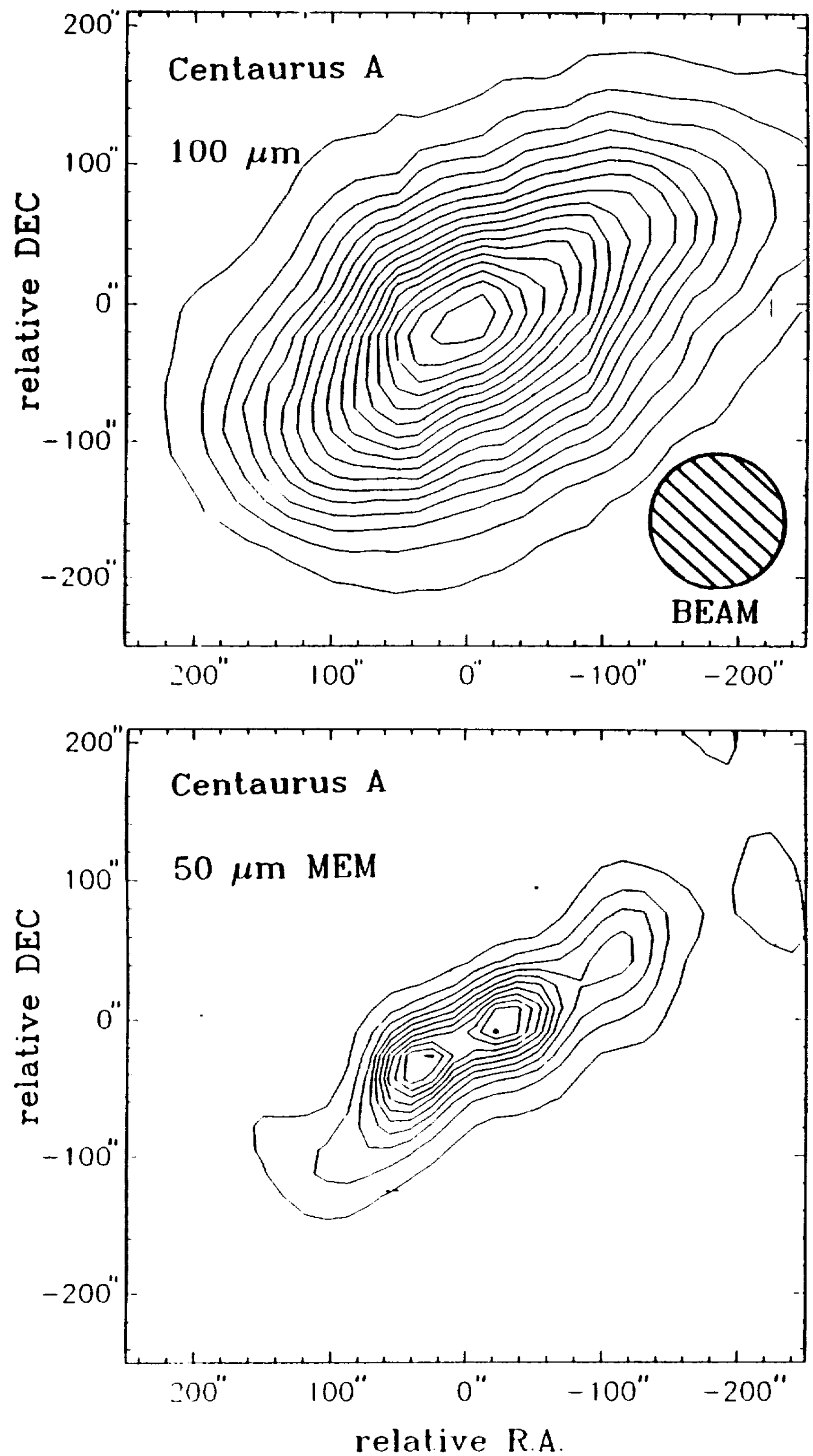


Fig. 3. Above: 100 μm map of Cen A taken by the IRAS CPC instrument. The lowest contour line is 6 % of the peak brightness of 581 MJy/sr. Below: 50 μm map taken by the same instrument and because of better signal to noise deconvolved by a maximum entropy method. The lowest contour line is 9 % of the peak brightness of 399 MJy/sr (Eckart et al., 1990a).

The nucleus of Cen A is both a strong radio-continuum (fig. 4) and X-ray source. Little is known about the nature of this source and there is a reasonable chance that it emits also gamma radiation providing the source is not too compact. Gamma radiation cannot coexist with high X-ray luminosity in a compact source (e.g. a neutron star) because of e^+, e^- pair production by interaction of gamma ray and X-ray photons (Herterich, 1974). The X-ray luminosity of Cen A is 4 orders of magnitude higher than Crab, but the question remains whether the source is compact enough that gamma radiation is shielded. From the observed variability of the X-ray source in the order of 3 years the upper limit of its size is 1 pc. The radio point source remains unresolved in the milliarc-second range (Kellermann, 1974; Shaffer and Schilizzi, 1975) corresponding to less than $4 \cdot 10^{16}$ cm.

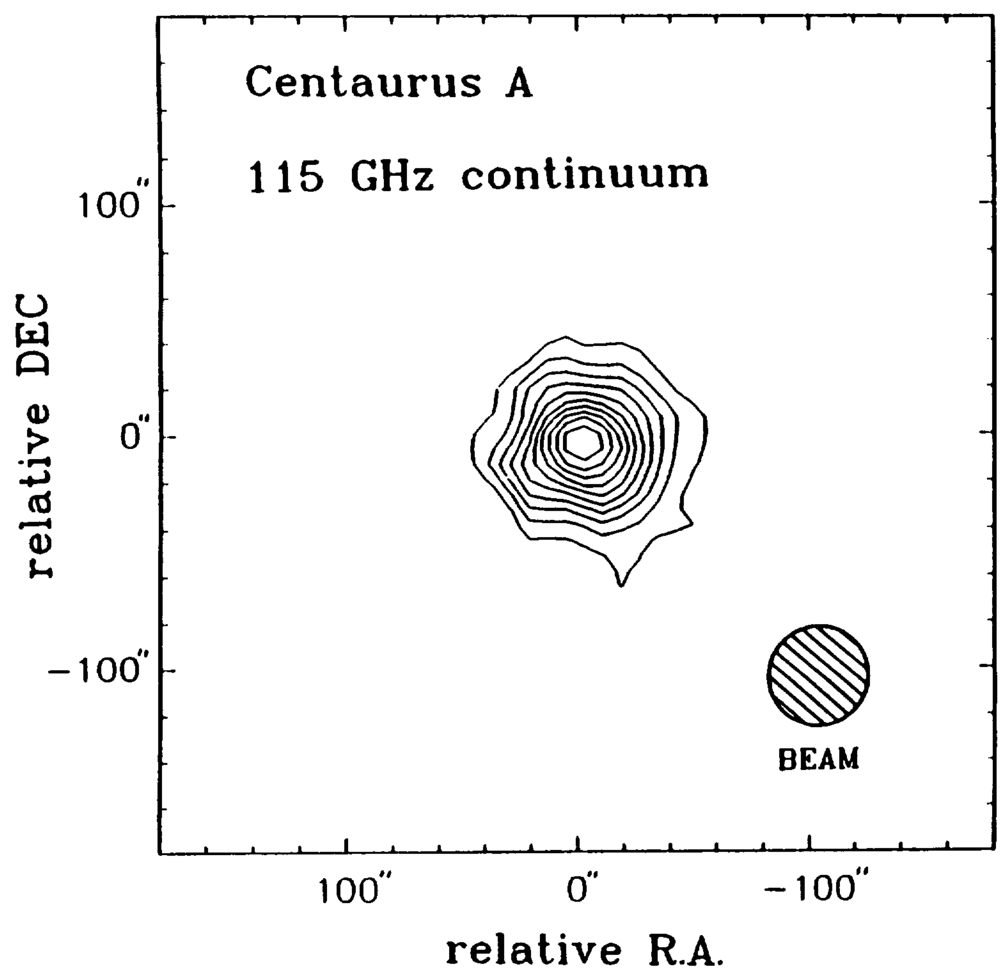
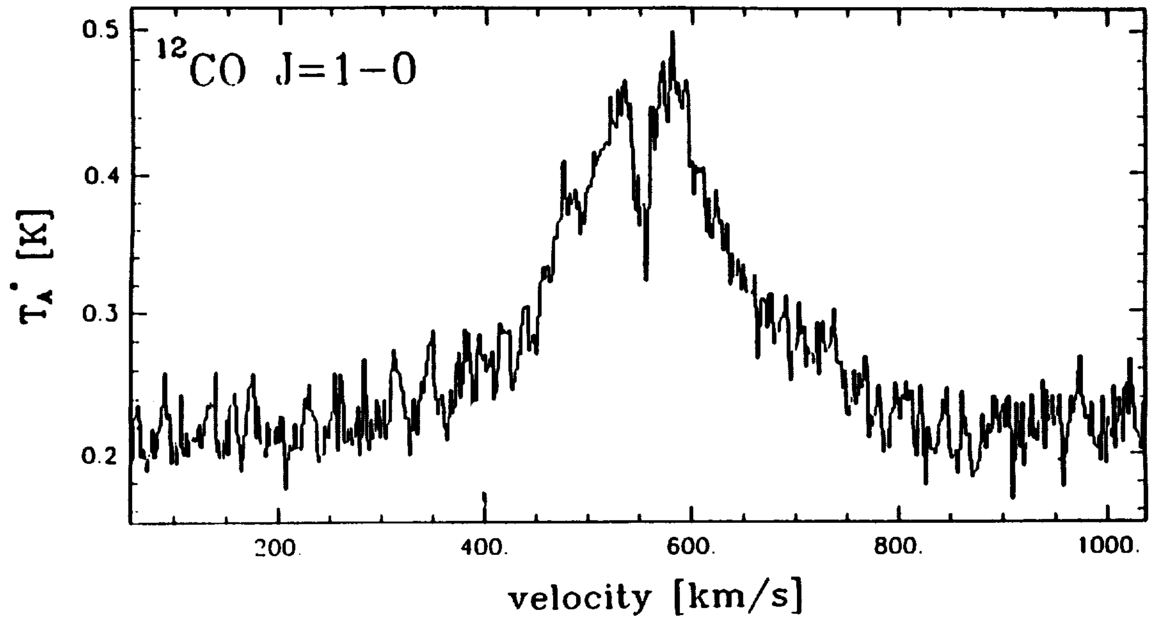


Fig. 4. Contour map of the 2.6 mm continuum emission of Cen A. This unresolved point source coincides with the nucleus of the galaxy (Eckart et al., 1990a).

Extinction of the low energy X-rays is not important as far as the measured luminosity of the source is concerned because 10 - 100 MeV photons would interact with the X-ray spectrum above 2 keV, but from the X-ray extinction below 2 keV a column density in the line of sight of 1.3



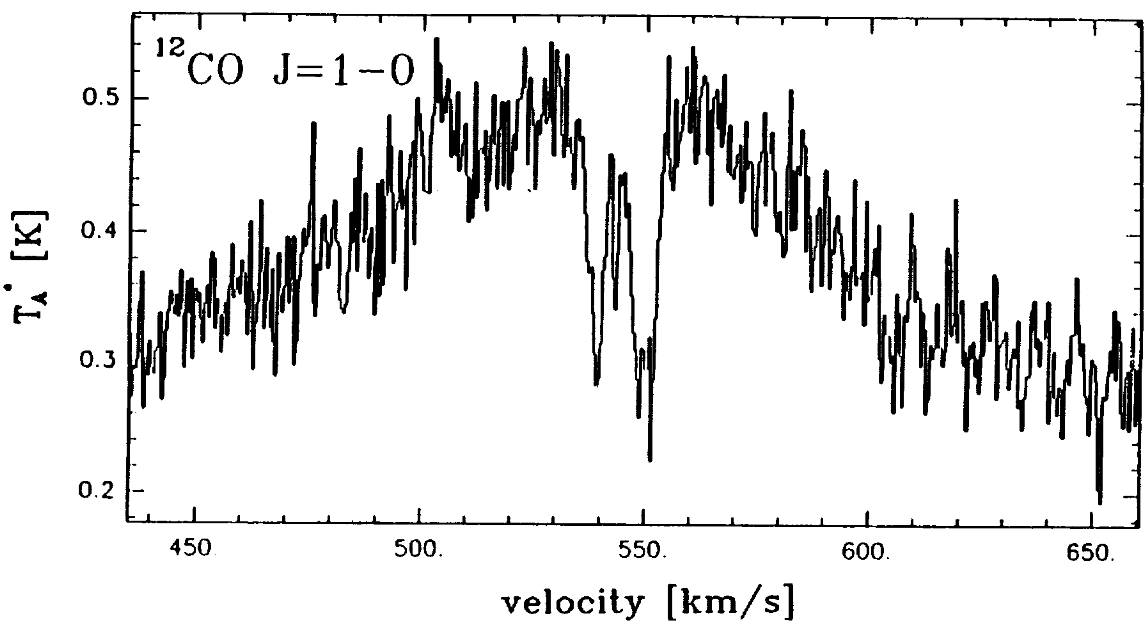


Fig. 5. 2.6 mm CO emission spectrum of Cen A towards the central continuum source. The spectrum appears on a flux density pedestal provided by the nuclear continuum source (5a) and the CO emission shows prominent absorption lines (better resolved at 5b) which are due to individual emitting molecular clouds, seen in absorption in front of a continuum point source of very high surface brightness (Eckart et al., 1990a).

$\cdot 10^{23}$ atoms/cm^2 (Stark et al., 1976) is derived. The column density towards the radio point source can be estimated independently in 2 ways:

a) The integrated CO emission towards the center of Cen A (fig. 2) is used to compile a density of $7 \cdot 10^{17}$ CO molecules/cm^2. Dividing by the relative abundance for dense galactic clouds of $8 \cdot 10^{-5}$ we get $9 \cdot 10^{21}$ H_2 molecules/cm^2 or $1.8 \cdot 10^{22}$ H atoms/cm^2 (Eckart et al., 1989 and 1990a). Adding $0.8 \cdot 10^{22}$ H atoms/cm^2 from the 21 cm HI observations (van Gorkom, 1987) and dividing by 2 because the source is in the middle of the emitting region, the total column density in the line of sight is $1.3 \cdot 10^{22}$ H atoms/cm^2.

b) Alternatively the H_2 column density can be evaluated from the CO line absorption of individual clouds in the line of sight towards the radio point source (fig. 5). (The lines of emitting clouds are seen in absorption because the point source has very high surface brightness). The strongest absorbing cloud has a density of $1 \cdot 10^{17}$ Co molecules/cm^2 (Eckart et al., 1990b) corresponding to $0.25 \cdot 10^{22}$ H atoms/cm^2. Fig. 5b reveals at least 3 clouds at different Doppler-shifts which implies a density of almost 10^{22} H atoms/cm^2. The amount of atomic hydrogene, measured in absorption (Van der Hulst et al., 1983) is only 10^{21} H atoms/cm^2 for a cloud and can be neglected.

Although both methods give roughly the same result, Method b seems to be more appropriate because it probes directly for matter in front of the radio point source. The fact that the column density observed in front of the radio source is 10-times smaller than the observed density in front of the X-ray source suggests that the X-ray source is smaller and deeper imbedded in absorbing material.

If the $r = 10^7$cm is a radius for a stellar X-ray source where photon-photon interaction is important (Heterich 1974), this must be scaled up for the nucleus of Cen A by the square root of the luminosity ratio (= 100) to a radius of 10^9 cm. This is comfortably below the upper limit for the diameter of the radio point source ($< 4 \cdot 10^{16}$ cm) and there is also no immediate conflict with a smaller size for the X-ray source, hence gamma radiation cannot be excluded by X-ray Gamma-ray absorption on grounds of so far available information.

IV. ACKNOWLEDGEMENT

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REFERENCES

Bhat, C.L., Issa, M.R., Houston, B.P., Mayer, C.J., and Wolfendale, A.W. 1985, Nature 314, 511.

Bhat, C.L., Mayer, C.J. and Wolfendale, A.W. 1986, Phil Trans. R. Soc. Lond., A 319, 249.

Black, J.H. and Fazio, G.G. 1973, Ap.J. (Letters), 185, L7.

Black, J.H. and Willner, S.P. 1984, Ap.J., 279, 673.

Blitz, L., Bloemen, J.B.G.M., Hermsen, W., and Bania, T.M. 1985, Astr. Ap., 143, 267.

Bloemen, J.B.G.M., Caraveo, P.A., Hermsen, W., Lebrun, F., Maddalena, R..J., Strong. A.W., and Thaddeus, P. 1984, Astr. Ap., 139, 37.

Bloemen, J.B.G.M., Strong, A.W., Blitz, L., Cohen, R.S., Dame, T.M., Grabelsky, D.A., Hermsen, W., Lebrun, F., Mayer-Hasselwander, H.A., and Thaddeus, P. 1986, Astr. Ap., 154, 25.

Cox, P., Mezger, P.G., Astron. & Astrophys. Rev. 1989, p. 49.

Eckart, A., Cameron, M., Rothermel, H., Wild, W., Zinnecker, H., Rydbeck, G., Olberg, M., Wicklind, T., ESO Workshop on Extranuclear Activity, Garching, FRG, May 1989.

Eckart, A., Cameron, M., Rothermel, H., Wild, W., Zinnecker, H., Rydbeck, G., Olberg, M., Wicklind, T. 1990a, Ap. J. (submitted).

Eckart, A. et al. 1990b (in preparation).

Grindlay, J.E. et al. 1975, Ap. J. (Letters), 197, L 9.
Herterich, K. 1974, Nature, 250, p. 311.
Hall, R.D. et al. 1976, Ap. J., 210, p. 631.
Kellermann, K.I. 1974, Ap. J. (Letters) 194, L 135.
Lebrun, F. et al. 1983, Ap. J., 274, 231.
Neugebauer, G., Habing, H.J., van Duinen, R., Aumann, H.H., Baud, B., Beichman, C.A., Beintema, D.A., Boggess, N., Clegg, P.E., de Jong, T., Emerson, J.P., Gautier, T.N., Gillett, F.C., Harris, S., Hauser, M.G., Houck, J.R., Jennings, R.E., Low, F.J., Marsden, P.L, Miley, G., Olnon, F.M., Pottasch, S.R., Raimond, E., Rowan-Robinson, M., Soifer, b.T., Walker, R.G., Wesselius, P.R., and Young, E., March 1984, Ap. J., 278, L1-L6.
Van der Hulst, J.M., Golish, W.F., Hashick, A.D. 1983, Ap. J. (Letters), 204, L37.
Van Dishoeck, E.F., Black, J.H. in G.E. Morfill and M. Scholer 1987 (eds.), Physical Processes in Interstellar Clouds, 241-274, D. Reidel Publishing Company.
Van Gorkom, J.H. 1987, IAU Symposium on Structure and Dynamics of Elliptical Galaxies, de Zeeuw, T. (ed.), 421.
Shaffer, D.B. and Schilizzi, R.T. 1975, Astron. J., 80, p. 753.
Stark, J.P., Davison, P.J.N., Culhane, J.L. 1976, Mon. Not. Astr. Soc. 194, Short Communication 35 P.
Tielens, A.G.G.M., Hollenbach, D. 1985, Ap. J. 291, 722.
Watson, D.M. 1982, XV. ESLAB Symposium on Galactic and Extragalactic Infrared Spectroscopy, Toledo, Spanien.
Young, J.S., Sanders, D.B. 1986, Ap. J. 302, 680